

2004 DOE Hydrogen, Fuel Cells & Infrastructure Technologies

Modeling and Control of a Solid Oxide Fuel Cell Auxiliary Power Unit

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This presentation does not contain any proprietary or confidential information

Objectives

SOFC-based APU development with a) control algorithms to optimize fuel efficiency and operating life, and b) models for stack response and structural failure under dynamic loading

► Controls

- Develop dynamic system models.
- Determine typical APU usage patterns.
- Collect electrical usage data from a working truck.
- Design control algorithms to optimize fuel efficiency and operating life.

► Shock & Vibration

- Identify failure modes under characteristic dynamic loading.
- Determine guidelines for durable SOFC/APU systems.
- Measure truck excitations and experimentally validate the models.
- Define requirements for APU isolation.

Budget

Fiscal Year	Activity	Funding
2003	Controls	\$300k
	Shock & Vibration	\$200k
2004	Controls	\$300k
	Shock & Vibration	\$200k

Technical Barriers and Targets

- ▶ DOE Technical Barriers for Transportation Systems and Fuel Cell Components
 - C. Thermal Management
 - D. Fuel Cell Power System Benchmarking
 - P. Durability
- ▶ DOE Technical Targets for Auxiliary Power Units
 - (2010) Efficiency: 35%
 - (2010) Cycle Capability: 500
 - (2015) Durability: 15,000 hours
 - (2010) Start-up Time: 15-30 minutes

Approach Controls Analysis

- ▶ Develop advanced algorithms to control an SOFC based APU system for long haul trucks. The controller seeks to optimize fuel efficiency and system operating life.
 - Create a dynamic system model of APU operation.
 - Use experimental validation to improve models.
 - Integrate APU, power electronics and control models into a single operating model.

Approach

Shock & Vibration Analysis

- ▶ Evaluate mechanical dynamics of APU
 - Simple, fast lumped parameter representation
- ▶ Evaluate dynamic response of SOFC stack
 - Assume stack is component most prone to damage
 - Detailed multi-cell stack finite element model
- ▶ Evaluate stresses in the stack against failure criteria to determine permissible accelerations
 - Permissible acceleration envelope is defined by criteria
- ▶ Measure excitation levels from truck frame
- ▶ Define APU isolation requirements based on expected excitations for Class VIII trucks

Approach

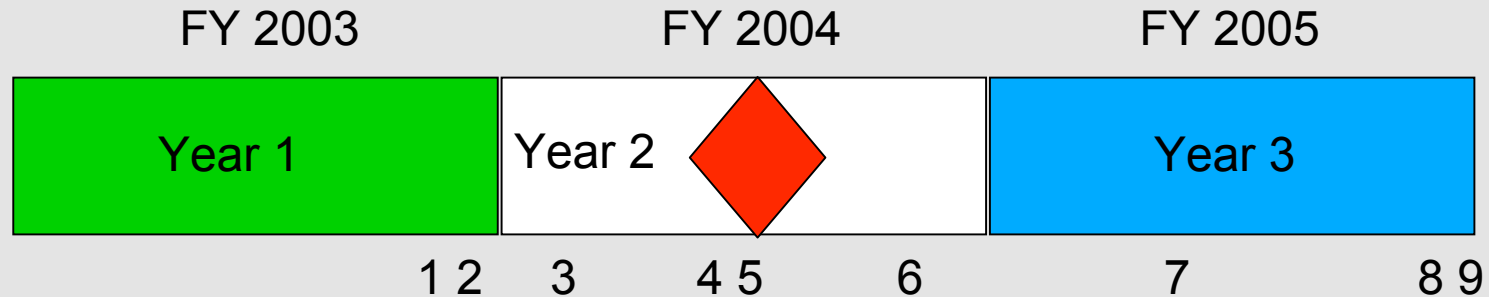
Shock & Vibration Analysis

- ▶ Thermal gradient stresses in stack are calculated for expected temperature distribution
- ▶ Dynamic stresses are calculated for unit excitation
- ▶ For elastic response, superposition is used to evaluate failure criteria:
 - Tensile stress-based: $\sigma_1^{fail} = \sigma_1^{thermal} + \beta\sigma_1^{dynamic}$
 - Fracture-based: $K_{1c} = K_1^{thermal} + \beta K_1^{dynamic}$
 - Displacement-based: $\delta_i^{fail} = \delta_i^{thermal} + \beta\delta_i^{dynamic}$
- λ β is then the limiting excitation level
- ▶ Criteria applied to PEN and rigid seal materials
- ▶ Developing interfacial seal fracture criterion

Project Safety

- ▶ Majority of project is modeling work performed on computers.
- ▶ In the model validation experiments performed, all relevant PNNL and DOE laboratory safety procedures were implemented and observed.
- ▶ The project has had zero recordable safety incidents.

Project Timeline



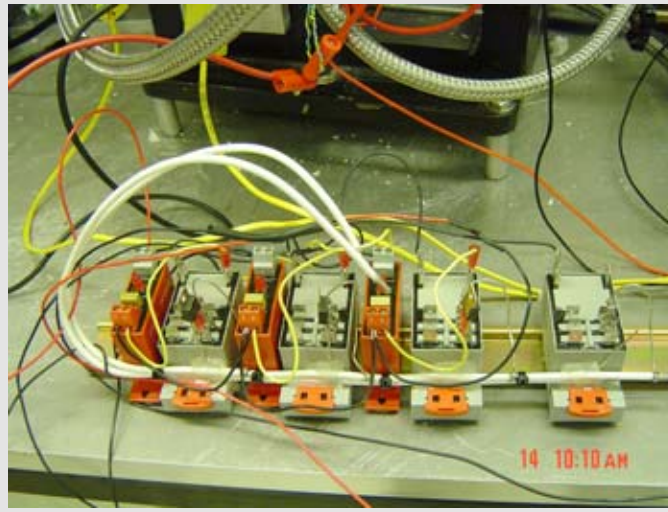
► Major Milestones

- Year 1
 1. Implement Initial System Controller – COMPLETE
 2. Initial Vibration Model Creation - COMPLETE
- Year 2
 3. Collect initial data for truck vibration and electrical usage - COMPLETE
 4. Create Models to Analyze Shock - COMPLETE
 5. Experimental Validation of Dynamic V-I Relationship – COMPLETE
 6. Complete Inclusion of Cyclic Loading in Interfacial Failure Models
- Year 3
 7. Shock, Vibration and Electrical Data Collection From Class VIII Truck APU
 8. Dynamic Bench Testing of APU/Stack for Durability and Isolation
 9. Extension of Controls to Full Truck Electrification

Stack Dynamic V-I Validation Experimental Setup



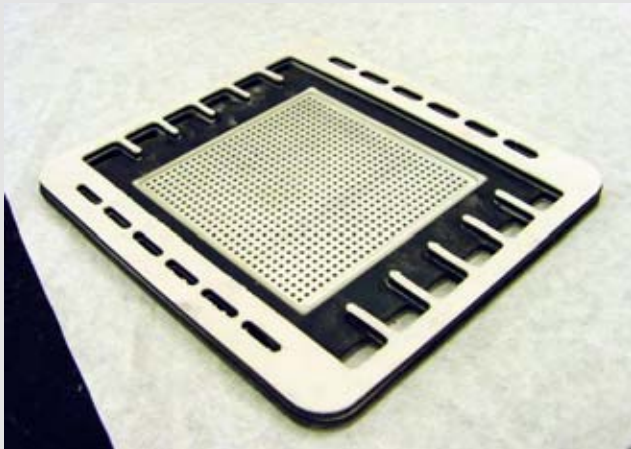
Fuel Cell Test Bed with Furnace, Fuel Source and Test Circuit



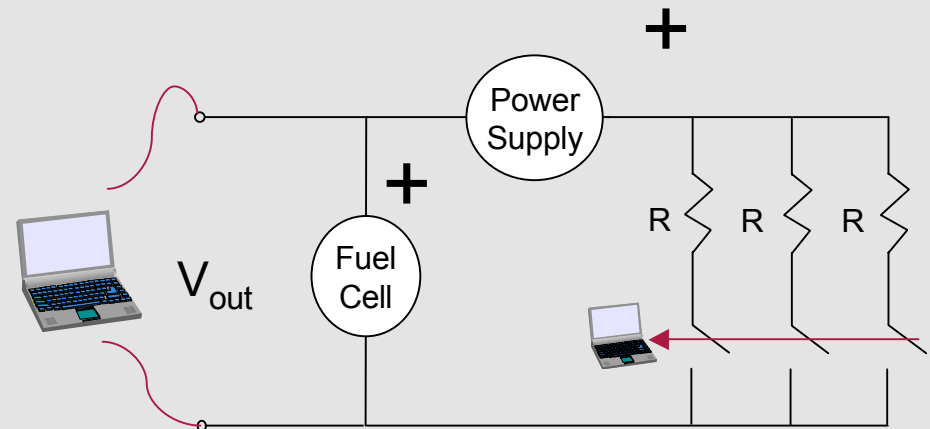
Close-up of test circuit



Cell with hearth plate



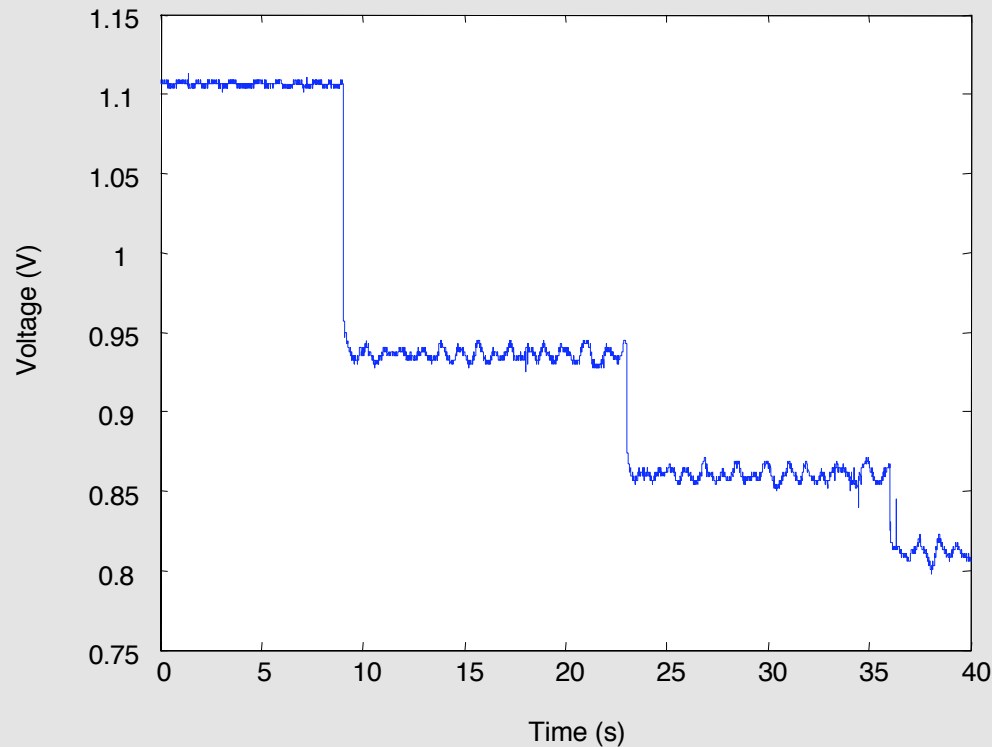
Cell before assembly



Experimental Circuit Schematic

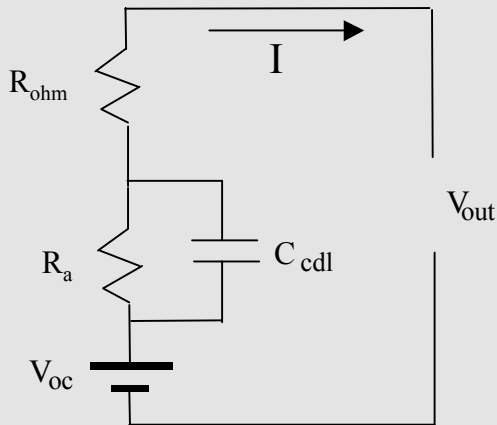
Raw Experimental Data

- ▶ Graph shows SOFC voltage versus time. The three load transitions are easily seen.



Dynamic V-I Relationship

Theoretical Model



Transfer Function

$$\frac{V_{oc} - V_{out}(s)}{I(s)} = \frac{R_a R_{ohm} C_{cdl} \cdot s + R_a + R_{ohm}}{R_a C_{cdl} \cdot s + 1}$$

V_{oc} = open circuit voltage

R_{ohm} = ohmic resistance through cell

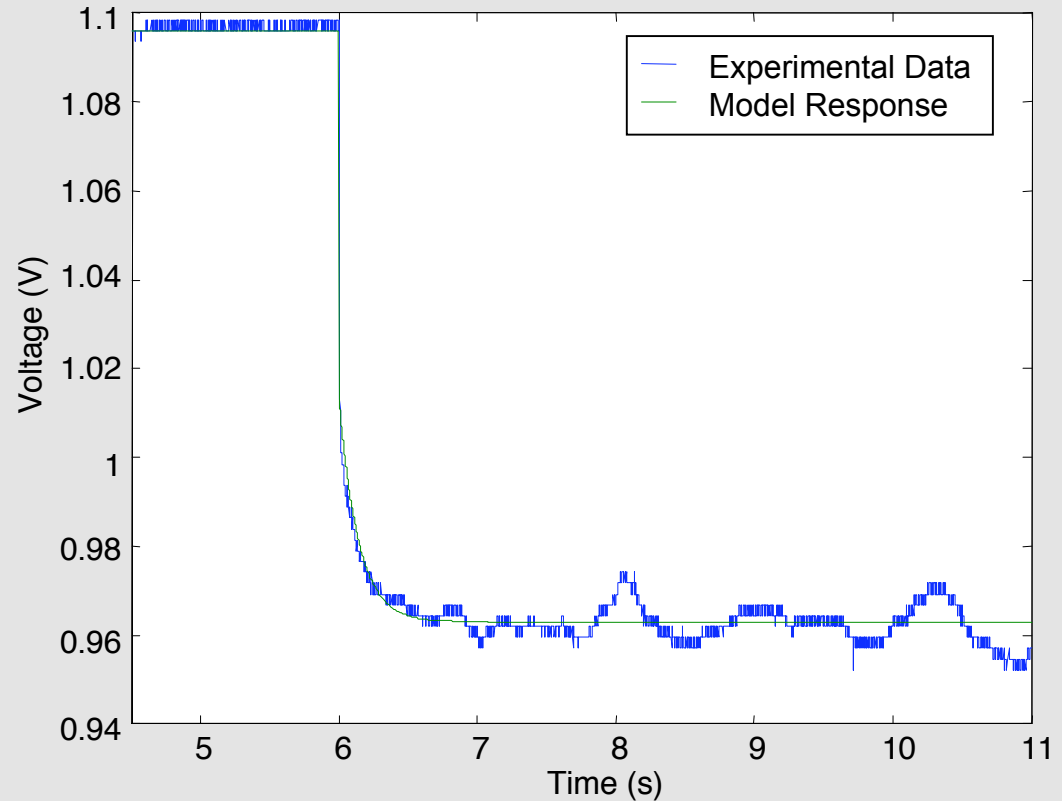
R_a = activation loss, caused by slowness of reaction

C_{cdl} = charge double layer effect capacitance

I = electrical current

s = Laplace variable

$$R_{ohm} = 0.0167\Omega \quad R_a = 0.0101\Omega \quad C_{cdl} = 13.8F$$



Actual Truck APU Load Data

- ▶ Through collaboration with PACCAR we received the following data on typical APU usage in a real truck

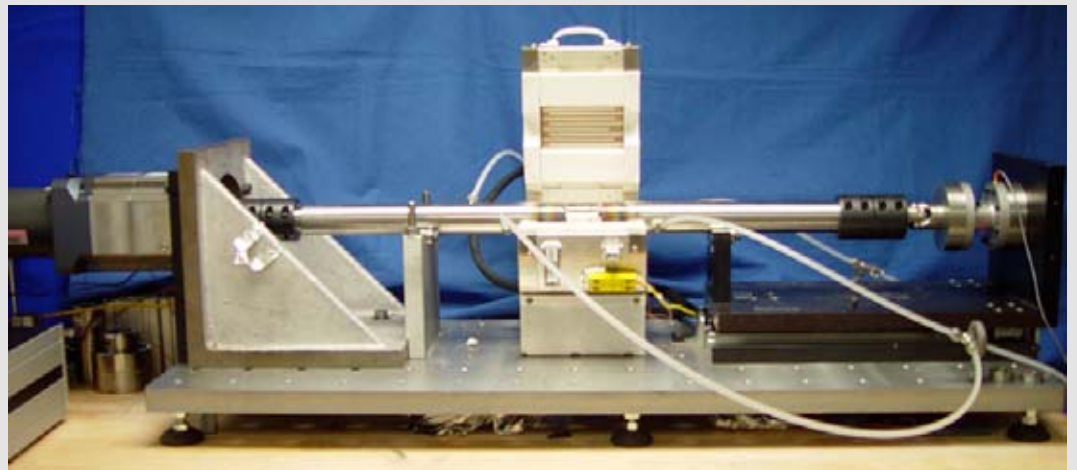
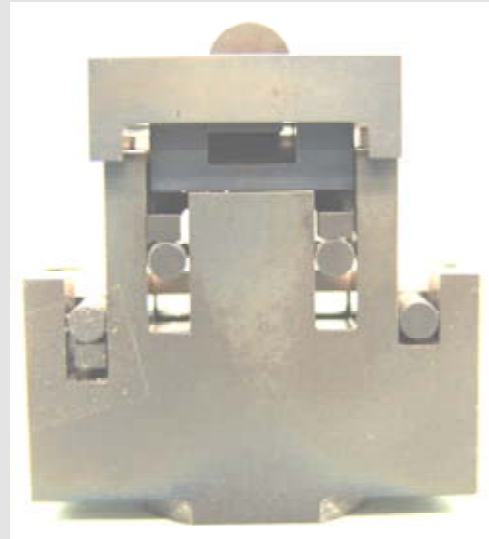
Source	Peak Load (watts)	Typical Load (watts)	Duty Cycle	Average Load (watts)
Audio System	350	50	25%	13
Television/VCR	75	75	15%	11
Satellite or Other Communication System	160	50	10%	5
Laptop Computer	65	65	25%	16
Microwave Oven	1400	1400	3%	42
Air Conditioning	4400	1700	70%	1190
Refrigerator	85	85	50%	43
Coffee Maker	250	250	2%	5
Lighting	100	60	50%	30
Miscellaneous	100	50	25%	13
Inverter Losses @ 15% of Load	300	290		20
TOTAL	7285	4075		1387

- ▶ We can use this data to show that an SOFC APU should be capable of providing 4075W steady state.
- ▶ The 3210W difference between typical and peak load can be made up with a battery or ultra-capacitor

Shock & Vibration Modeling Progress

Materials Testing

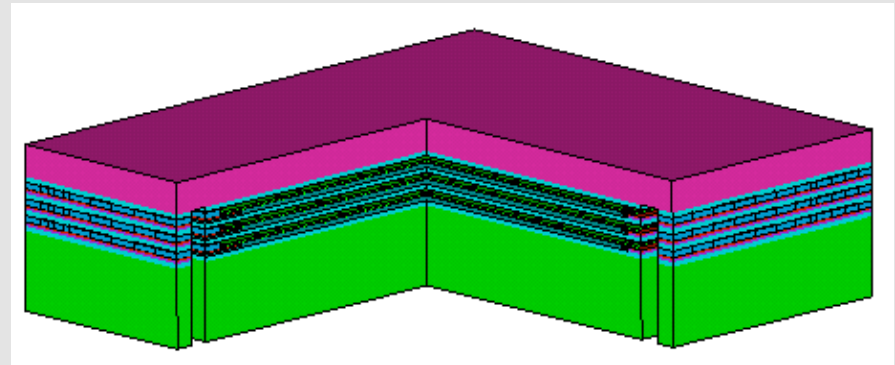
- ▶ Working with PNNL's SECA CTP team to determine elevated temperature strength and failure properties of seal materials for use in failure criteria
- ▶ Materials
 - G18 Glass
- ▶ Test methods
 - 4-point bend
 - Tension
 - Torsion



Shock & Vibration Modeling Progress

- ▶ Improved dynamic analysis capabilities
 - Modal (pre-stressed)
 - Harmonic
 - Spectrum response
 - Random vibration
 - Shock transient*
 - Multiple excitations/directions
- ▶ Added failure criteria
 - Component tensile stress
 - Anode fracture
 - Interfacial fracture in progress

3-cell planar stack

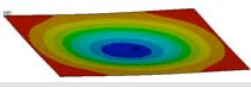
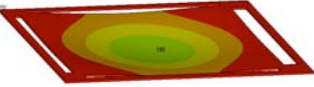

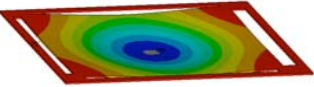
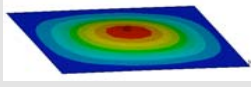

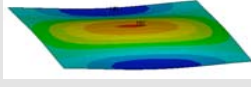
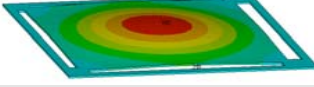
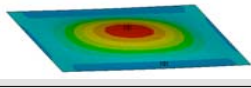

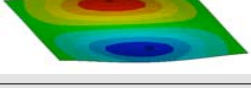

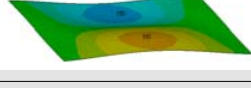
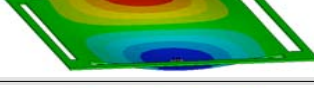




- ▶ Improved material properties and strengths obtained from SECA CTP
- ▶ Existing experimental data obtained for truck APU* and frame vibration amplitudes

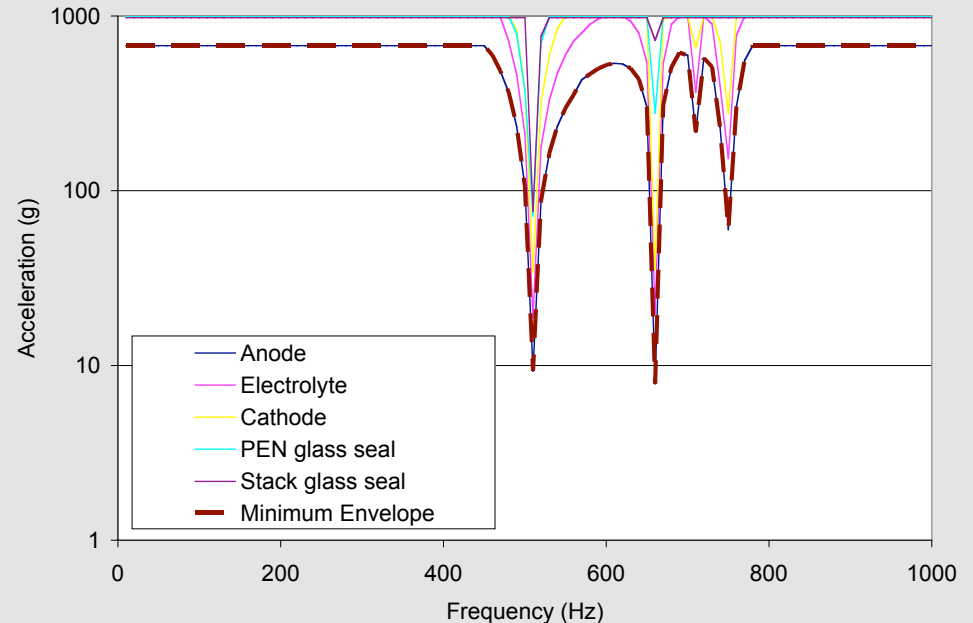
*milestone

Shock & Vibration Modeling Progress

Modal Response of 3-cell stack

Freq	PEN UZ	Interconnect UZ
522		
567		
661		
709		
749		
843		
847		
936		

Permissible Acceleration Envelope

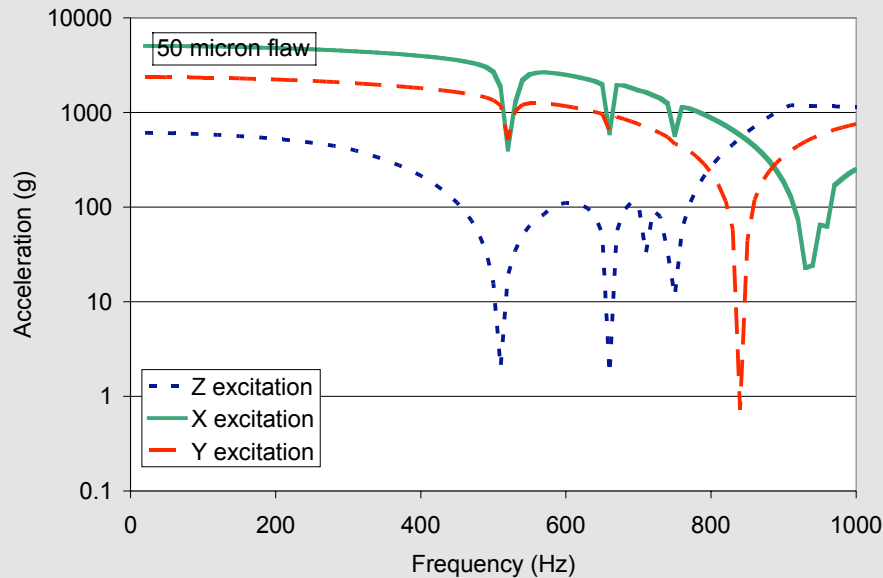


► Acceleration envelope

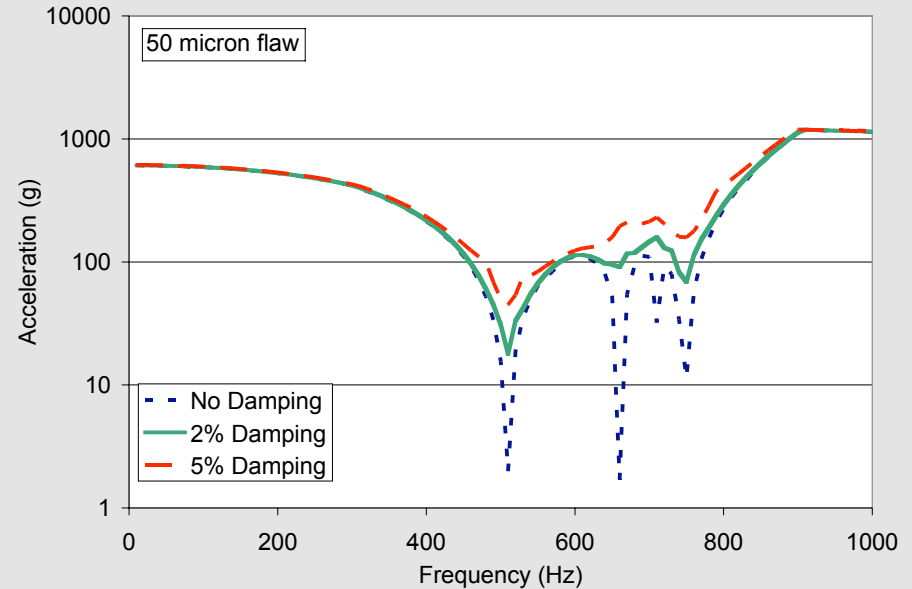
- Defined by union of failure criteria
- Response is limiting at coupled resonant frequencies of the PEN and interconnect (10-1000 Hz)

Shock & Vibration Modeling Progress

Permissible Accelerations



Permissible Accelerations



► Excitation direction

- Validates amplitude criteria needed for 3 axes
- Different modes excited, so cell orientation important

► Damping

- Significant influence on response so must include conservative estimates for SOFC materials

Interactions and Collaborations

- ▶ PACCAR: Rich Bergstrand, provided experimental APU electrical usage and vibration data.
- ▶ Delphi: Steve Shaffer, providing assistance in model validation experiments including shaker table tests.
- ▶ Univ of Illinois, Chicago: Sudip Mazumder, collaboration in the modeling and design of power conversion electronics.
- ▶ Georgia Tech: Jianmin Qu, provided cell fracture models.
- ▶ SECA-CTP: Use of material data and constitutive models developed under Core Technology Program.

Responses to Previous Year Reviewers' Comments

- ▶ Develop strong integration with SECA
 - Working with PNNL and ORNL materials developers to get necessary mechanical data on seals and anodes.
 - Utilizing constitutive and fracture models developed under SECA Core Technology Program. In-progress leak model also of interest.
 - Performed dynamic V-I tests on a SECA funded cell.
- ▶ Demonstrate interest of industry
 - Using PACCAR provided data for power usage and component vibration.
 - Delphi to provide shaker table facilities for model validation tests.
- ▶ Perform experimental validation
 - Tested transient response of SOFC to validate dynamic voltage-current transfer function.

Conclusions

- ▶ The predominant V-I transfer function has one real pole and one zero, yielding a response without overshoot or oscillation.
- ▶ The dynamic response is being added to PNNL's SOFC system model.
- ▶ Working with University of Illinois, Chicago to design power conditioning electronics based on the dynamic V-I model developed here.
- ▶ Vibration models predict permissible acceleration envelope from multiple elastic failure criteria for PEN and seals.
- ▶ Acceleration limits needed for different orientations due to planar stack sensitivity to loading direction.
- ▶ Will continue to work with PACCAR to collect more detailed truck APU data for electrical usage (load vs. time) and expected vibrations (amplitude and frequency content).

Future Work

► Remainder of FY 2004

- Define optimization equation for system fuel efficiency.
- Incorporate power electronics model from Univ of Illinois.
- Add failure criteria to shock analysis procedures.
- Integrate interface fracture criteria with FEA model.
- Define APU isolation requirements.

► FY 2005

- Collection of APU electrical usage data from working truck.
- Extension of system model and controls to full truck electrification.
- Data collection for Class VIII truck shock & vibration.
- Vibration testing of instrumented stack.